Solar Spectroscopy: Ultraviolet and Extreme Ultraviolet Emission

Vacuum ultraviolet (VUV) emission is defined as that electromagnetic radiation with wavelengths shorter than 2000 Å. Its name comes from the fact that light shorter than 2000 Å is strongly absorbed by most gases and, in particular, the atmosphere. VUV is usually divided into far ultraviolet (FUV) extending from 1200 to 2000 Å and the extreme ultraviolet (EUV) in the range 300 to 1200 Å. The spectral features of these wavelengths will be discussed with the focus on the spectral emission lines. Continuum radiation will only be discussed briefly. One can ask why is it interesting to observe the VUV emission from the Sun? There are several important reasons for this as it provides important information on:

- physical properties of the solar and stellar atmospheres
- fundamental mechanisms responsible for heating the corona and accelerating the solar wind
- how VUV variability alters the dynamics and chemistry of the Earth's upper atmosphere
- possible influence on the Earth's climate due to variations in the VUV irradiance from the Sun.

In this article the main focus will be on the first two items while the latter two are discussed in more detail elsewhere (see EARTH'S ATMOSPHERE, SOLAR IRRADIANCE, SOLAR–TERRESTRIAL CONNECTION: LONG-TERM AND SHORT-TERM CLIMATE VARIABILITY.

Historical background of VUV observations

The solar ultraviolet (FUV) and extreme ultraviolet (EUV) emission contain a number of strong emission lines and continua well suited for quantitative plasma diagnostics of the solar atmosphere. Our entire knowledge of temperatures, densities, emission measures, mass motions and elemental abundances comes from high-resolution spectral observations in the vacuum ultraviolet.

The VUV wavelength range is absorbed by oxygen and ozone in the Earth's atmosphere and hence is totally inaccessible to even the largest ground-based telescopes. Below 2000 Å the radiation dissociates molecular oxygen in the upper atmosphere, indirectly resulting in the formation of ozone (O_3). To observe the Sun, stars and other celestial objects in this wavelength range, the instruments must be carried above the absorbing atmosphere by means of sounding rockets, Earth satellites or space vehicles. Space astronomy started in 1946 in the United States when captured V-2 rockets became available to navy scientists for use as free-flying, high-altitude observatories. It was not surprising, under these circumstances, that a group from the US Naval Research Laboratory (NRL) in Washington, DC, became the first to observe the Sun's ultraviolet radiation with a spectrograph mounted on the tail fin of a V-2 rocket. Since then much progress has been made in solar high-resolution spectroscopy from space (see SPACE INSTRUMENTATION, SPECTROGRAPHS: HIGH-RESOLUTION SPECTROGRAPHS). A large number of experiments have been launched to observe the EUV and UV portions of the solar spectrum.

Measurements of the solar UV spectral energy distribution are often divided into two groups. Some instruments use only a spectrometer and observe the spectral irradiance of the integrated solar disk. The irradiance measurements are designed to study the Sun's radiant energy output and its variability, and thus require very high photometric accuracy and instrument stability. Other instruments employ an imaging device followed by the spectrometer and observe the radiance from a limited area of the solar disk. The primary goal with the radiance measurements is to differentiate between various emitting regions on the Sun. However, it is much more difficult to achieve high photometric accuracy because of the more complex optics and the often larger number of reflecting surfaces.

Calibration and instrument degradation

Quantitative measurements of the properties of the solar gas should be carried out from intensity calibrated spectra. Even without an absolute calibration one can extract useful information from the spectral data such as the shapes of spectral lines, their wavelength positions as well as line ratios. However, to determine how many photons actually entered the instrument from the Sun an absolute calibration needs to be applied where the reflectivity of each optical element of the instrument needs to be accounted for. The fact that the reflectivity of the coatings used in UV/EUV instruments often degrades with time complicates the calibration effort.

Ultraviolet intensity measurements are particularly difficult because the very solar radiation to be measured with high precision is itself the main cause of instrument degradation. The effect is attributed to contamination by organic material, which is outgassing from materials used in the instrument design and is subsequently photoactivated and deposited on irradiated surfaces. The process, although now well understood, is very difficult to prevent in complex optical instruments for space flight. Comprehensive cleanliness control programs during integration of the instruments are used to reduce degradation. Most EUV/UV instruments still suffer from some sensitivity losses during their operation. Thus, intercalibration between different instruments, both on satellites and rocket payloads, is being used to determine the absolute level of emission from single features on the Sun.

VUV emission lines

The high-temperature solar atmosphere is the only astrophysical plasma source that can be studied with high spatial resolution. Much of our understanding of STELLAR ATMOSPHERES is based on the understanding of plasma processes that occur in the upper solar atmosphere.

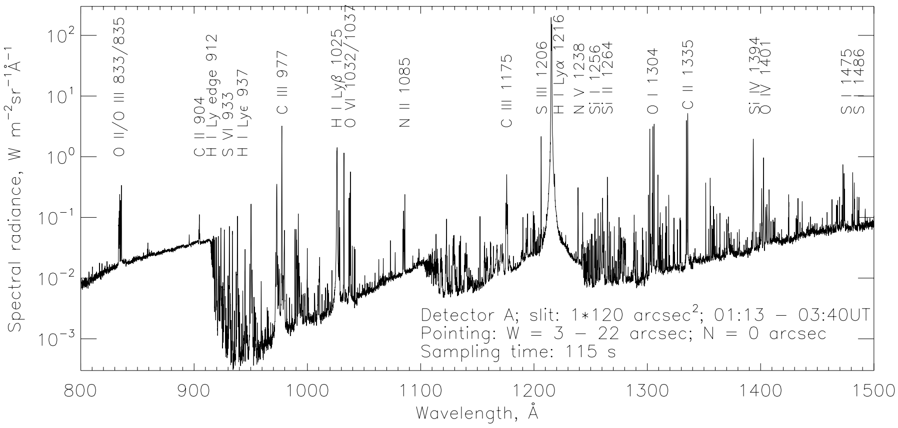

Figure 1. Quiet Sun spectrum from 800 Å to 1500 Å shown as spectral radiance. Selected prominent emission features are identified.

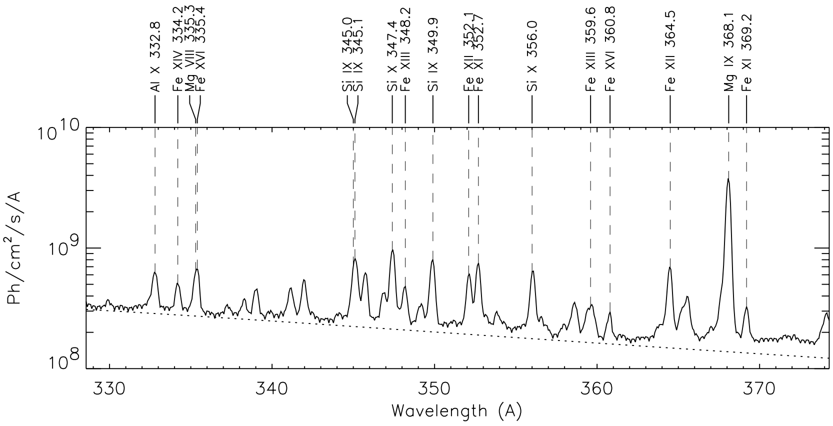

Figure 2. Integrated spectrum of the Sun observed with the normal incidence spectrometer (NIS) on CDS showing a number of highly ionized emission lines. The irradiance spectrum was derived by adding the emission from 690 different exposures distributed over the solar disk.

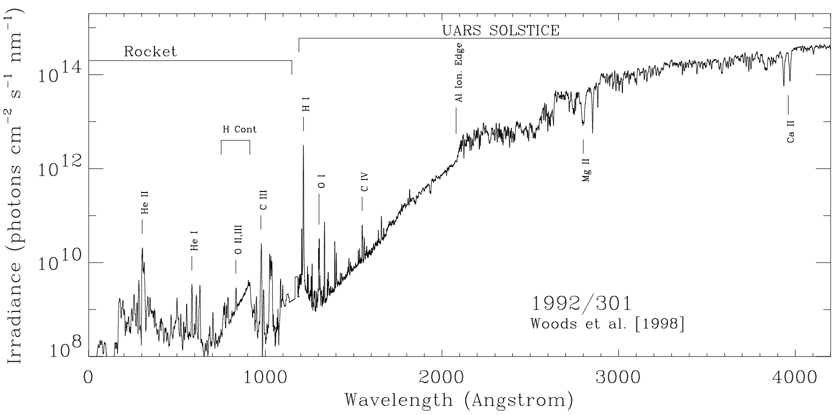

Figure 3. Solar VUV irradiance spectrum obtained with a LASP/NASA rocket instrument ($\lambda \leq 1200$ Å) and by the UARS/SOLSTICE instrument ($\lambda \geq 1200$ Å). At longer wavelengths the spectrum is dominated by the continuum emission and absorption lines while at shorter wavelengths the spectrum is dominated by emission lines.

Although some of the plasma processes can be studied by high-resolution images of the solar atmosphere much of our knowledge on temperatures, densities, emission measures, mass motions and elemental abundances comes from high-resolution spectral observations in the far ultraviolet (VUV) to the x-ray wavelength range (2000–1.7 Å).

The solar spectrum in the range 1150–1700 Å contains a large number of bright lines, mainly from plasmas of the CHROMOSPHERE and the lower TRANSITION REGION, i.e. at electron temperatures $T_e \leq 2.5 \times 10^5$ K. However, no lines from the upper transition region ($2.5 \times 10^5 \leq T_e \leq 1 \times 10^6$) are strong enough to be observed, and only a few lines originating at coronal temperatures appear mainly in PLAGES and LIMB spectra. In comparison, the solar spectrum in the range 100–1150 Å includes a large number of lines from the upper transition region and CORONA in addition to lines from the chromosphere and lower transition region.

At wavelengths longward of 1150 Å high spectral and spatial resolutions were achieved by several instruments. In the UV wavelength range there are in particular two instruments that made great impact on solar spectroscopy: the NRL/SO82B EUV spectrograph on Skylab ATM (Apollo Telescope Mount) and the NRL/High Resolution Telescope and Spectrograph (HRTS). More than 3000 emission lines have been observed in the 1150–1700 Å spectral range by these instruments and most of them have been identified. At shorter wavelengths, however, the spectral and spatial resolution was relatively poor and only the strongest lines could be identified. Recent observations with EUV spectrometers on the Solar and Heliospheric Observatory (SOHO) have greatly improved our knowledge about the emission at shorter wavelengths down to 150 Å. The Coronal Diagnostic Spectrometer (CDS) and the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) complement each other since CDS relies heavily on diagnostics to determine the physical parameters in the solar corona and SUMER is designed to study the dynamical aspects of the chromosphere, transition region and corona in more detail. Selected line ratios give the electron temperature and the electron density. Absolute line intensities provide the differential emission line (DEM) distribution, the ion and elemental abundances. The line shift and broadening give information about dynamical phenomena of the emission plasma.

The SUMER spectrometer can observe emission lines in the spectral range 500–1600 Å. Figure 1 shows the quiet Sun spectral radiance spectrum from 800 Å to 1500 Å shown as spectral radiance. Selected prominent emission features are identified. In particular the wavelength range below 1175 Å has never before been observed with such high spectral resolution, and it contains a wealth of spectroscopic detail. More than 1000 emission lines have been observed and many of them have been recorded for the first time. About 98% of the observed spectral features have been identified. SUMER provided for the first time detailed information of high members of the hydrogen Lyman series which are important not only for understanding properties of the solar chromosphere but also of the O I excitation process in the Earth's atmosphere. SUMER is also the first instrument to provide comprehensive spectroscopic information on the solar corona above the limb out to two solar radii. In contrast to past observations, where only a very small number of lines were observed above the limb, more than 600 coronal emission lines have been observed in the quiet corona by SUMER, from which about 400 are still unidentified.

CDS is a dual extreme ultraviolet (EUV) spectrometer covering most of the wavelength range 150–780 Å. It has given the first detailed observations of this wavelength range with higher spectral, spatial and temporal resolution than previous instruments. The different wavelength bands have been carefully selected to cover useful spectroscopic diagnostic lines. An example of a quiet Sun spectrum observed with the normal incidence spectrometer on CDS is illustrated in figure 2. The wavelength range (310–380 Å) is dominated by Mg IX 368 Å and a number of lines from highly ionized ions, in particular from iron. A number of line pairs in this band are useful for density diagnostics using ratios such as the Si X 347/356, Si IX 345/349 and Fe XIII 359/348 lines.

Continuum emission

The UV radiation emitted by the Sun between 1400 Å and 1680 Å originates from the temperature minimum region and the low chromosphere according to calculated model atmospheres. The absolute value of the continuum intensity in the spectral range around 1600 Å is important since it reflects the value of the temperature minimum used in model calculations of the solar atmosphere.

The quiet solar radiation shortward of 1680 Å is primarily due to free–bound transitions from lower lying energy levels of neutral silicon in the temperature minimum region, about 500 km above $\tau_{5000} = 1$ according to model calculations. At wavelengths shorter than 1521 Å the emission is almost entirely caused by recombination to the ground state ($3p^2\ ^3P$) with smaller contribution to the emission from C I and from the Ly_α wing. At wavelengths longer than 1521 Å recombination to the first excited level ($3p^2\ ^1D$) of Si I is the main source of emission together with Fe I and Mg I. Ultraviolet line emission from higher temperatures (and heights) also contributes to the photoionization rate of neutral silicon in the temperature-minimum region. For quiet Sun conditions this contribution is small but is greatly increased during flares.

The continuum emission at shorter wavelengths is also a useful diagnostic tool. The C I, H I and He I continua have upper bounds of 1100 Å, 911 Å and 504 Å respectively. However, few observations of this weak continuum emission have been made until recently when the improved instrument sensitivity on the SOHO satellite became available. The H-continuum (also called the Lyman-continuum) is fairly free from emission lines as can be seen in figure 1. The C I continuum shortward of 1008 Å is contaminated by the He I continuum which tends to appear in the spectral second order of the grating.

Spectral irradiance and solar variability

Only about 1% of the Sun's total energy is emitted at VUV wavelengths less than 3000 Å, while approximately 50% is emitted between 4000 and 8000 Å. However, the variability in the VUV portion of the Sun's spectrum exceeds that at visible wavelengths and contributes significantly to the solar irradiance variability in spite of its minor contribution to the total irradiance itself (see SOLAR IRRADIANCE for more details). The VUV radiation is furthermore the dominant source of energy for heating and ionization in the terrestrial upper atmosphere at altitudes above 90 km. Thus, a good knowledge of the solar EUV spectral irradiance is of critical importance for many analyses of the photochemistry and energy balance of the ionosphere and the thermosphere. Solar UV light is primarily responsible for both creation and destruction of ozone in the Earth's stratosphere and mesosphere (see OZONE HOLE). Stratospheric ozone densities are known to vary with the 11-year SOLAR CYCLE. Solar variability over the solar cycle also causes expansion and contraction of the outward extension of the Earth's atmosphere into space. Thus, satellites in low orbit will feel an increased drag when the Sun is active and the result is reduced lifetime. Another important issue is that changes in the Earth's upper atmosphere induced by variations in solar UV radiation could affect the surface climate through feedback mechanisms. It is therefore important to obtain a reliable specification of the Sun's radiative output variability in order to isolate anthropogenic global changes from natural variability.

Bibliography

For further reading about the VUV emission a few selected pointers to key books and papers are listed below.

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P Brekke